View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Queensland University of Technology ePrints Archive

QUT Digital Repository:
http://eprints.qut.edu.au/

This is the accepted version of this conference paper. To be published as:

Senadeera, Wijitha (2010) *A quasi-stationary approach to drying kinetics of different shaped food particulates in a heat pump assisted by fluid bed dryer*. In: Chemeca 2010 : Engineering at the Edge, 26-29 September 2010, Adelaide. (In Press)

© **Copyright 2010 Please consult the author.**

A QUASI-STATIONARY APPROACH TO DRYING KINETICS OF DIFFERENT SHAPED FOOD PARTICULATES IN A HEAT PUMP ASSISTED FLUID BED DRYER

Wijitha Senadeera

School of Engineering Systems
Queensland University of Technology
2 George Street GPO Box 2434
Brisbane QLD 4001
Australia
w3.senadeera@qut.edu.au

ABSTRACT

Experiments were undertaken to study drying kinetics of different shaped moist food particulates during heat pump assisted fluidised bed drying. Three particular geometrical shapes of parallelepiped, cylindrical and spheres were selected from potatoes (aspect ratio = 1:1, 2:1, 3:1), cut beans (length: diameter = 1:1, 2:1, 3:1) and peas respectively. A batch fluidised bed dryer connected to a heat pump system was used for the experimentation. A Heat pump and fluid bed combination was used to increase overall energy efficiency and achieve higher drying rates. Drying kinetics, were evaluated with non-dimensional moisture at three different drying temperatures of 30, 40 and 50^{o} C. Due to complex hydrodynamics of the fluidised beds, drying kinetics are dryer or material specific. Numerous mathematical models can be used to calculate drying kinetics ranging from analytical models with simplified assumptions to empirical models built by regression using experimental data. Empirical models are commonly used for various food materials due to their simpler approach. However problems in accuracy, limits the applications of empirical models. Some limitations of empirical models could be reduced by using semi-empirical models based on heat and mass transfer of the drying operation. One such method is the quasi-stationary approach. In this study, a modified quasi-stationary approach was used to model drying kinetics of the cylindrical food particles at three drying temperatures.

Keywords: Shaped foods, fluid bed, heat pump, drying, quasi-stationary

INTRODUCTION

Drying of foods is a major operation in the food industry, consuming large quantities of energy. Dried foods are stable under ambient conditions, easy to handle, possess extended storage life and can be easily incorporated during food formulation and preparation. The drying operation is used either as a primary process for preservation, or a secondary process in certain product manufacturing operations. Drying is a complex process and involves simultaneous mass and heat transfer accompanied by physical and structural changes (Fusco et al., 1991). These changes will influence drying characteristics of the materials. Also the quality of food material undergoing drying depends on their initial quality, and changes occurring during drying. Shape and size of the products change appreciably, influencing their physical properties, which in turn modify final texture and transport properties of the dry foods (Karel, 1991, Senadeera et al., 1998).

Among different drying methods, fluidized bed drying is recognized as a gentle, uniform drying, down to very low *residual moisture* content, with a high degree of efficiency (Borgotte et al., 1981). This is a very convenient method for heat sensitive food materials as it prevents them from overheating (Gibert et al., 1980, Giner and Calvelo, 1987). The fluidized bed drying for granular materials is now established and many driers are operating throughout the world in the chemical and food industries. The properties of particulate materials relate to the type of fluidization technique (Shilton and Niranjan, 1993). The application of this technique is best suited to smaller and spherical particles. The disadvantages of this method include entrainment of friable solids by the gas and limited application to larger and poorly fluidized materials.

Heat pumps have been known to be energy efficient when using in drying operations. The principal advantages of heat pump dryers are their latent heat recovery, better control of drying temperature and humidity. Any dryer that uses convection as the primary mode of heat input can be fitted with a suitably designed heat pump such as fluid bed dryers. Heat pump fluidised bed drying offers a better product quality, offsetting incremental increasing in drying cost with a higher market value for the product (Alves-Filho and Strommen, 1996).

Knowledge of drying kinetics is important in the design, simulation and optimisation of drying processes. Drying curves are usually expressed by empirical models defining drying rate constants based on first order kinetics built by regression using experimental data and depend on the shape of the products (Senadeera et al., 2003). Empirical models are commonly used for various food materials due to their simpler approach. However problems in accuracy, limits the applications of empirical models. Some limitations of empirical models could be reduced by using semi-empirical models based on heat and mass transfer of the drying operation.

Some limitations of the empirical models derived to describe drying characteristics could be eliminated by using a semi-empirical approach. Such a method is the modified quasi-stationary method (Efremov, 1999). The model is based on mass conduction of solid materials in bulk, given in terms of effective moisture diffusivity, resulting in the following semi-theoretical equation for drying kinetics;

$$MR = \frac{m - m_e}{m_i - m_e} = \frac{1}{1 + \left(\frac{t}{\sigma}\right)^p} \tag{1}$$

Where, MR – dimensionless moisture, m – moisture at given time (kg/kg db), m_e – equilibrium moisture (kg/kg db), m_i – initial moisture content, t-drying time (h), σ – characteristic time (h) and p – hydrodynamic intensity

The objective of this study is to describe drying kinetics of different shaped food particulates at three drying temperatures using a quasi-stationary approach, in a heat pump assisted batch type fluid bed dryer and study the effect of particle shape on the parameters of the drying kinetic equation.

MATERIAL AND METHODS

Material preparation

Beans

Fresh green beans *Phaseolus vulgaris* of the variety Labrador was used for producing cylindrical particles. Beans were purchased from the same supplier to maximize reproducibility of results. Care was taken when selecting the size of beans to obtain a consistent diameter of 10$\pm$1 mm. Size was measured using vernier caliper with an accuracy of 0.05 mm. Both ends of the beans were removed and only the middle portions, which resemble a cylindrical shape, were used to produce the required samples. Samples were prepared at three length to diameter ratios of 1:1, 2:1 and 3:1. After cutting, beans were kept in a plastic container in a cold room at 4^0 C for more than 24 hours until drying commence. Twenty five kg of beans were needed for each experiment.

Potato

Potato *Solanum tuberosum* of the variety Sebago was washed and brushed to remove skin and mud. Washed potato was pushed through a stainless steel square cutter to make parallelepipeds with aspect ratio of 3:1, 2:1and 1:1, the particles were cut carefully to lengths of 19.5, 13 and 6.5 mm respectively. After cutting, beans were kept in a plastic container in a cold room at 4^0 C for more than 24 hours until drying commence. Twenty five kg of beans were needed for each experiment.

Green peas

Fresh green peas *Pisum sativum* of the variety Bounty were shelled by hand and graded using a wire mesh and those with average diameter 10 $\pm$ 1 mm were selected. All samples were stored in a cold room for 24 hours at 4^o C until drying commence.

Moisture content determination

Moisture content was determined by measuring the loss in weight of finely chopped samples held at 70^0 C and 13.3 Kpa vacuum for 24 hours (AOAC, 1995).

Volume Measurement

The volume of the particles was measured by the liquid displacement method using liquid paraffin (SG = 0.8787 at 30^o C) as the medium, using a measuring cylinder of 22 mm inside diameter and 50 ml capacity.

Drying in a fluidised bed

One batch stored in the cold room was taken for fluidised bed drying experimentation. Fluidised bed dryer was connected to the heat pump dehumidifier system (Figure 1). The drying conditions of 30^0 C, 40^0 C and 50^0 C were set by the temperature controller in the heat pump dehumidifier system, and the drying set up was run for 2 hours to achieve steady state conditions of drying before material introduction. Initial bed height of 150 mm was used. The hot air velocity passing through the material bed was kept at a constant value of 2.2 m/s for all drying experiments. This velocity was selected, because it was within the limit of fluidisation and terminal velocity of all three materials concerned and within the capability of the fan. The air-flow entering the dryer was controlled by flow control valves. Samples were collected from the dryer at 30 minutes intervals through the sample outlet. Each time they were collected in a sealable container and immediately used for moisture determination and volume measurements.

Fig. 1: Heat pump assisted fluid bed dryer

ANALYSIS OF EXPERIMENTAL DATA AND MODELLING PROCEDURE

The modified quasi-stationary model has been used to describe the drying kinetics of cylindrical particulate materials that dry mostly in the falling rate period. The parameters σ and p were estimated using Matlab (2009) Curve Fitting Tool Box on a personal computer.

RESULTS AND DISCUSSION

Beans

Table 1 shows the value p (Index of Hydrodynamic Intensity) in equation 1, which is a representation of hydrodynamic condition of the bed during drying experimentation for different L:D ratios.

Tab. 1: Index of hydrodynamic intensity (p) for different L:D ratios

L:D Ratio	p
1:1	1.75
2:1	1.75
3:1	1.69

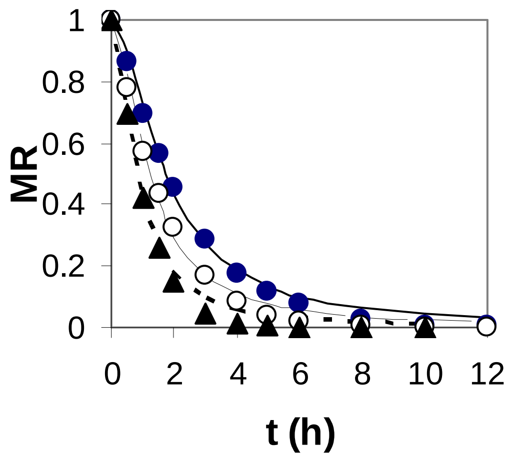
From the values given in Table 1 it was observed that Hydrodynamic intensity (p) of the fluidized bed is same for the ratios of L:D = 1:1 and 2:1, but different for 3:1. This may be due to different shrinkage behaviour of the material showed at different drying temperatures for different L:D ratios, which is related to drying kinetics (Senadeera, 2008). Another reason could be channeling and slugging behaviour of the particles at higher initial moisture contents which is more prominent at higher L:D ratio where lower value of Index of Hydrodynamic Intensity showed . Also it can be both material shape and aerodynamic of the bed dependent. Table 2 shows the characteristic times (σ) for different L:D ratios and drying conditions

Tab. 2: Characteristic time (σ) for different L:D ratios at drying temperatures

L:D Ratio	30^oC	40^oC	50^oC
1:1	1.719	1.215	0.8374
2:1	2.796	1.862	1.162
3:1	5.602	2.689	1.624

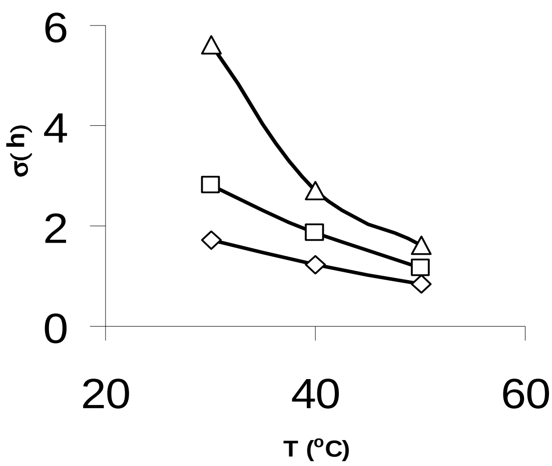
Figure 2 represents a comparison of the predicted curves with experimental drying kinetics obtained for cylindrical particles with L:D = 1:1, dried at constant air velocity of 2.2 m/s at three different drying temperatures. The regular spread of experimental points along the respective predicted curves indicated that Equation 1 describes well the drying kinetics (L:D = 2:1 and 3:1 predicted curves and experimental drying kinetics are not shown).

Figure 3 shows graphical representation of change in value of the characteristic time with temperature for different L:D ratios. In all L:D ratios, characteristic drying time reduced with increased temperature. For L:D = 1:1 and 2:1, a linear reduction was shown with drying temperature but L:D = 3:1 showed non-linear trend. This non-linear reduction could be attributed to irregular moisture removal through diffusion as a result of irregular fluidisation behaviour observed accompanied with slugging and channelling.



• 30°C ○ 40°C ▲ 50°C

Fig. 2: Drying kinetics of L:D = 1:1 at drying temperatures



∆ L:D = 3:1 □ L:D = 2:1 ◊ L:D = 1:1

Fig. 3: Characteristic drying times (σ) with drying temperatures for different L:D ratios

Potato

Table 3 and 4 shows value p (Index of Hydrodynamic Intensity) in equation 1, which is a representation of hydrodynamic condition of the bed during drying experimentation for different L:D ratios and the characteristic times (σ) for different aspect ratios and drying conditions.

Tab. 3: Index of hydrodynamic intensity (p) for different aspect ratios

Aspect Ratio	**p**
1:1	1.81
2:1	1.69
3:1	1.67

Tab. 4: Characteristic time for different aspect ratios at drying temperatures

	30°C	**40°C**	**50°C**
1:1	0.9268	0.7814	0.5797
2:1	1.059	0.9392	0.7720
3:1	1.122	1.038	0.7920

For all aspect ratios, characteristic drying time reduced with increased temperature in a linear fashion. This linear behaviour could be attributed to similar moisture removal patterns through diffusion due to their homogenous structure with absence of skin. Variations among the values observed may be due to irregular fluidisation behaviour accompanied with slugging and channelling. Higher Hydrodynamic intensity value at aspect ratio 1:1 showed as a result of good fluidisation quality compared to other aspect ratios.

Peas

Table 5 shows value p (Index of Hydrodynamic Intensity) and characteristic drying time in equation 1 for Peas. Similar to other material shapes (cylindrical and parallelepiped) characteristic drying time reduced with temperature and Index of hydrodynamic intensity varies between 1.726 $\pm$ 0.101 showing similar hydrodynamic conditions in the drier system for all temperatures. Variations observed in the values may be attributed to different shrinkage behaviour observed at different drying temperatures.

A good agreement between experimental and predicted values ($R^2 > 0.98$) showed that the hydrodynamic conditions of the heat pump assisted fluidised bed drying of particles with three L:D ratios properly reflected by the relatively high index of hydrodynamic intensity.

Tab. 5: Index of hydrodynamic intensity (p) and Characteristic time for Peas

	30°C	**40°C**	**50°C**
p	1.714	1.682	1.783
σ	3.659	2.268	1.280

Also it was observed that characteristic drying time corresponds to the drying air temperatures decreased linearly with increased temperature for all particles considered. Slight variation in predicted and experimental values showed variation in true material temperature which is not equal to the drying air temperature. Hydrodynamic intensity value is similar for all particle shapes and sizes at drying temperatures considered.

CONCLUSIONS

The index of hydrodynamic intensity (p) correlates well with the experimental points for a particular size and shape of the materials considered at different drying temperatures. It is reasonable to conclude that application of a modified quasi-stationary method describes the drying kinetics well. The characteristic drying time decreased with increased drying temperatures for all particle shapes and sizes. Slight variations resulted in values may have attributed to quality of fluidisation existed inside the drying system.

NOTATION

D	diameter	(m)
L	length	(m)
m	moisture content (dry basis)	(kg/kg db)
MR	dimensionless moisture	
p	hydrodynamic intensity	
t	drying time	(h)
T	drying temperature	(°C)

Greek Symbols

σ	characteristic drying time	(h)

Subscripts

e	equilibrium
o	initial

REFERENCES

Alves-fiho, O. & Strommen, I 1996, Performance and improvement in heat pump dryers. *Drying 96*, edited by Strumillo, C., and Pakowski, Z., Krakow, Poland, pp. 405-415.

AOAC 1995, Official Methods of Analysis. 16th edition, Association of Official Analytical Chemists, Washington DC.

Borgolte, G. & Simon, EJ 1981, Fluid bed processes in the manufacture of snack products, CEB review for chocolate, *Confectionary and Bakery*. Vol. 6, no.2, pp. 7-8, 10.

Efremov, GI 1999, A Modified Quasistationary Method of Describing the Kinetics of Drying of Hygroscopic Materials. *Journal of Engineering Physics and Thermophysics*, Vol. 72, no. 3, pp. 396-400.

Fusco, AJ, Avanza, JR, Aguerre, RJ & Gabritto, JF 1991, A diffusion model for drying with volume change, *Drying Technology*, Vol. 9, no. 2, pp. 397-417.

Gibert, H, Baxerres, JL, & Kim, H 1980, Blanching time in fluidized beds. In Food *Process Engineering 1: Food Processing Systems*, (P. Linko, Y. Malkki, J. Olkku and J. Larinkari eds) pp. 75- 85, Applied Science Publishers, London.

Giner, SA, & Calvelo, A 1987, Modelling of wheat drying in fluidized beds, *Journal of Food Science*, Vol. 52, no. 5, pp. 1358- 1363.

Karel, M 1991, Physical structure and quality of dehydrated food, In: *Drying'91*, AS, Mujumdar and I Filkova (Ed.), pp. 26-35, Elsevier Science Publishers, Amsterdam.

Matlab 7.6., 2008, *The Language of Technical Computing*, The Mathworks Inc., USA

Senadeera, W 2008, The drying constant and its effect on the shrinkage constant of different shaped food particulates, *International Journal of Food Engineering*, Vol. 4, No. 8, article 14.

Senadeera, W, Bhandari, BR, Young, G and Wijesinghe, B 1998, Change of physical propeties of green beans during drying and its influence on fluidisation. In '*Drying'98* Volume B-Proceedings of the 11th International Drying Symposium, Halkidiki, Greece, Eds. C. B. Akitidis, D. Marinos-Kouris & G. D. Saravakos, Ziti Editions, thesssaloniki, Greece: 1139-1146.

Senadeera, W, Bhandari, BR, Young, G & Wijesinghe, B 2003, Influence of shapes of selected vegetable materials on drying kinetics during fluidized bed drying, *Journal of Food Engineering*, Vol. 58, pp. 277-283.

Shilton, NC & Niranjan, K 1993, Fluidization and its Applications to food processing, *Food Structure*, Vol. 12, pp.199- 215.